1. Introduction

Nanotechnology is a new subject focusing on nanoscale world, which was first proposed by American physicist Richard Feynman in a speech in 1959 [1-2]. Nanotechnology is an extension of sciences and technologies that deal with particles less than 100 nm (Figure 1) [3–5]. Because of fine particle sizes, nanomaterials have unique structural characteristics compared with traditional materials for soil reinforcements. Nanomaterials can produce four effects (i.e., size, quantum, surface and interface effect) and have been widely used in the fields of information, materials, energy, environment, medical and health, biology and agriculture [6]. There are two approaches, i.e., macroscopic materials broken down into nanometer-sized substances (top-down) and atomic or molecular components reconstructed into nanomaterials (bottom-up) (Figure 2) [7]. With rapid development of nanotechnology and superior performance of nanomaterials, nanomaterials (e.g., Nano silica, Nano clay, Nano alumina, nano-titania and nanotubes) have been introduced to improve subgrade and pavement materials. The use of nanomaterials in subgrade and pavement engineering is very significant since nanomaterials can modify various types of construction materials and additives. In subgrade engineering, seasonal repeated rainfall puts the subgrade under cyclic drying/wetting conditions, which leads to continuous disintegration and strength degradation of subgrade rocks and soils [8–10]. Previous studies [11–14] have shown that cyclic drying/wetting can cause shear strength reduction and excessive wetting deformation of geomaterials (Figure 3). Nanotechnology provides a means for building durable and low-maintenance highway infrastructure [15]. In subgrade engineering, nanotechnology is usually applied in two aspects: (1) analysis of soil structure from nanoscale to better reveal the subgrade performance mechanism with diverse nanostructures; (2) improvement of performance of subgrade soils from nanoscale by using nanomaterials as admixtures [16–18]. In pavement engineering, nanotechnology is mainly applied to flexible pavements and concrete pavements. The viscosity, rutting and fatigue resistances of asphalt mixtures are often enhanced deeply by adding nanoparticles [19]. The existence of nanoscale pozzolans, for instance, Nano silica, can help to achieve more dense microstructural packing and more impermeable cement matrix [20]. The mechanical properties (e.g., compressive strength, flexural strength, tensile strength) and durability (e.g., abrasion resistivity, freezing–thawing resistance) of concrete can be enhanced by Nano silica [21]. Although many studies have been conducted to improve material properties with nanomaterials
in civil engineering, there is still lack of review work on application of nanomaterials in subgrade and pavement engineering.

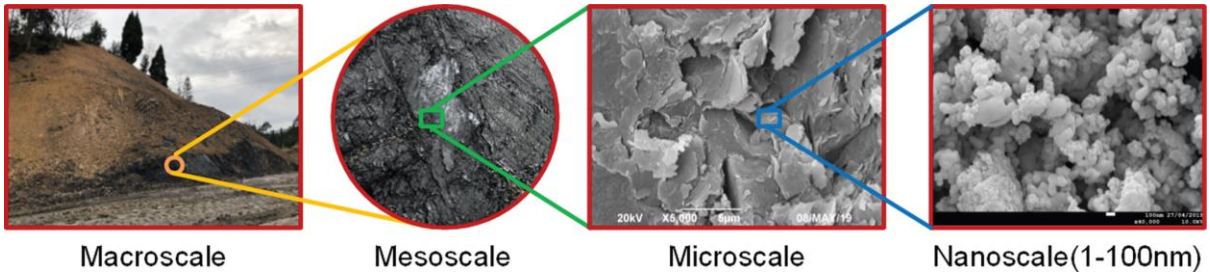


Figure 1. Soils viewed at different scales.

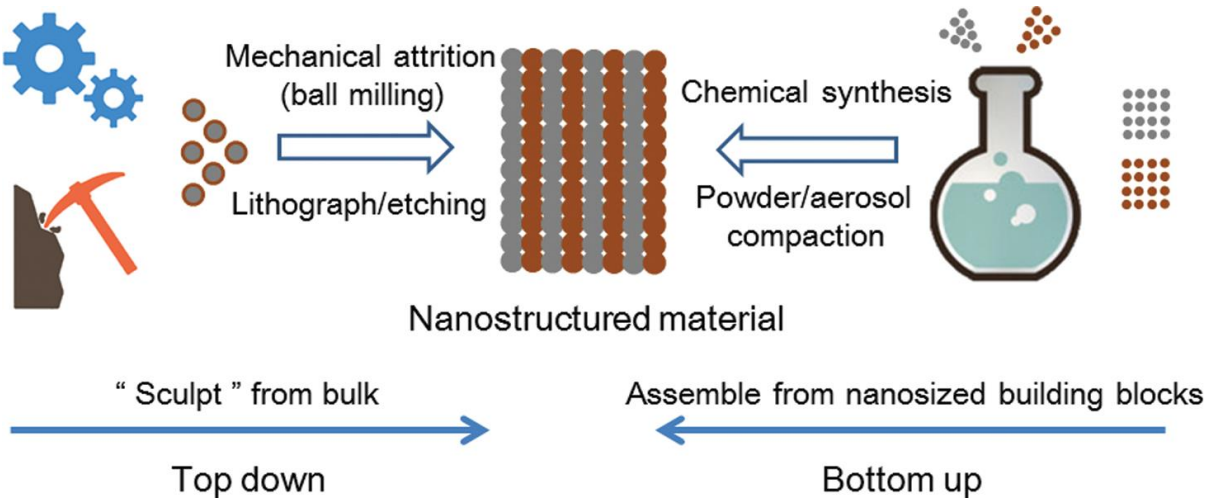


Figure 2. Synthesis and assembly approaches for nanostructured material.

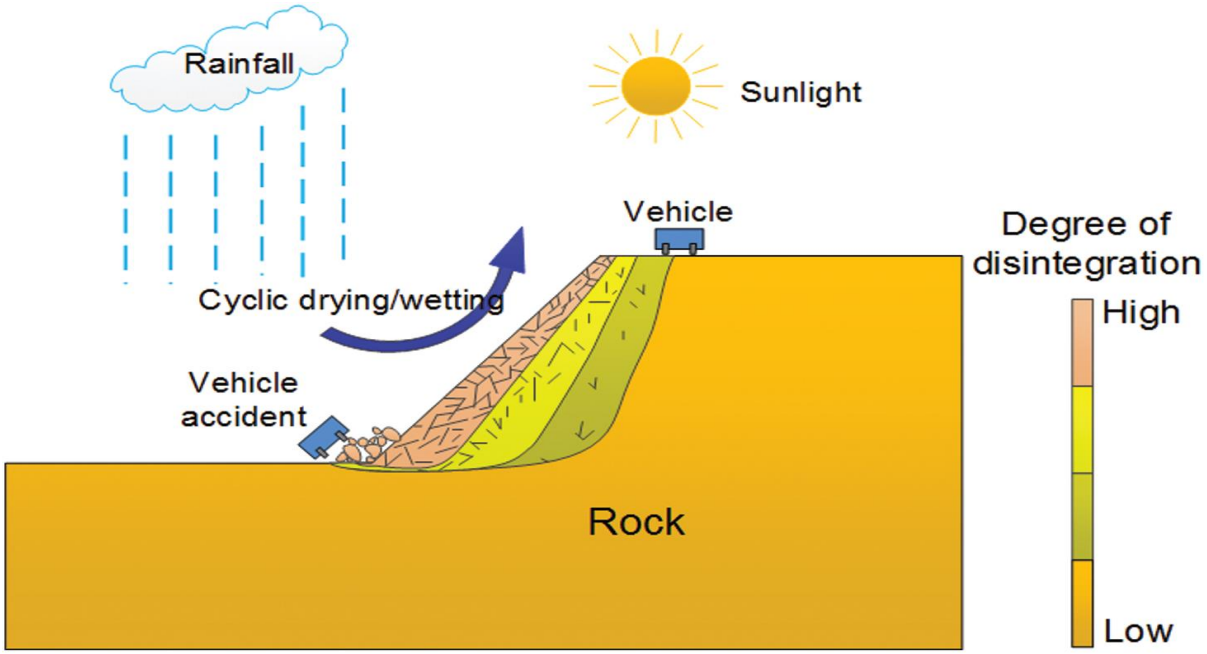


Figure 3. Schematic diagram of instability of an embankment slope.

2. Problem Statement

It is known that due to isomorphous substitution, clay particles consist of superficial negative charges [22-23]. As a result, electrostatic forces exist between the negative clay surface and exchangeable cations within the clay-pore fluid media whose strength is dependent on the chemistry of the exchangeable cation [22]. In order to maintain neutrality within the clay-pore fluid media, there is a natural affinity for the counter ions to be attracted onto the surface of clay particles, thereby decreasing their concentration with distance from the clay surface. This change in concentration produces the surface electrostatic property known as the diffuse double

layer, and the amount of cations needed for maintenance of neutrality on the clay surface is the cation exchange capacity [24]. The double layer consequently causes a separation between the minerals and particles, accompanied by swelling behaviour [22] for expandable clay minerals like montmorillonite. It is obvious that the diffuse double layer significantly influences all the engineering properties of clayey soil, especially the hydraulic conductivity [25]. Expansion of the diffuse double layer thickness is expected to reduce the hydraulic conductivity and the converse is the case when the double layer is decreased [26]. This in essence provides the framework for the swell-shrink behaviour of expansive soils with moisture variation (Figure 4).

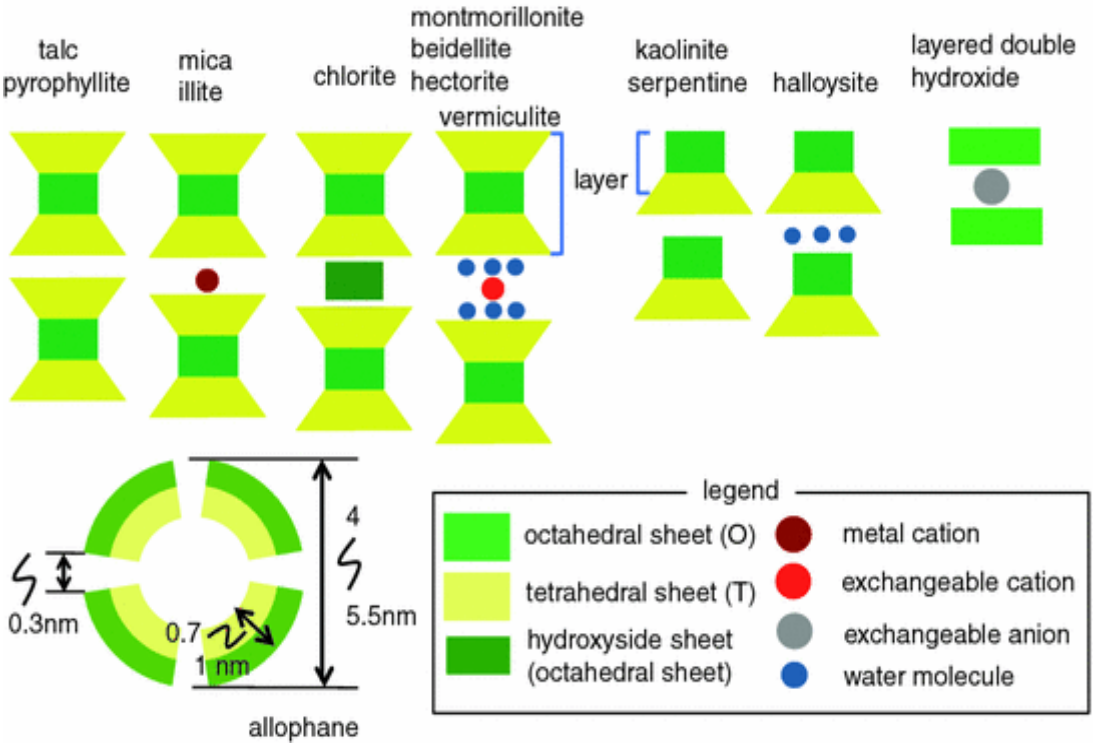


Figure 4. Nano clay Minerals and Problem Statement in Subgrade

Therefore, how to accurately determine the physicochemical reactions according to the types of subgrade soil, Nano-clay is one of key issues for future to research on nanomaterials as improved subgrade soil.

3. Literature Review

3.1 Fabrication and Characterization of Composite Nanomaterials

Various approaches are available for each of the three synthesis methods, namely solution-blending (Figure 5), Melt-blending (Figure 6) and in-situ polymerization (Figure 7). An important task in the preparation of polymer/Nano clay composites is to achieve a uniform dispersion of Nano clay in the polymer matrix. The solution-blending technique often yields favorable dispersion of clay layers in the polymer matrix, in comparison with melt blending, due to its low viscosity and high agitation power. On the other hand, melt blending is considered industrially viable and ecofriendly, with high economic potential [27]. The in-situ polymerization method is a widely-applied synthesis technique, which provides uniform dispersion and is easy to modify by changing the polymerization conditions [28]. Recently, a number of novel synthesis approaches have been proposed to design polymer/Nano clay composites with unique properties. In this work, different advanced synthesis approaches are reviewed and relationships between the synthesis strategy, the structure formation, physical and mechanical properties and characteristics of the polymer/Nano clay composites are discussed.

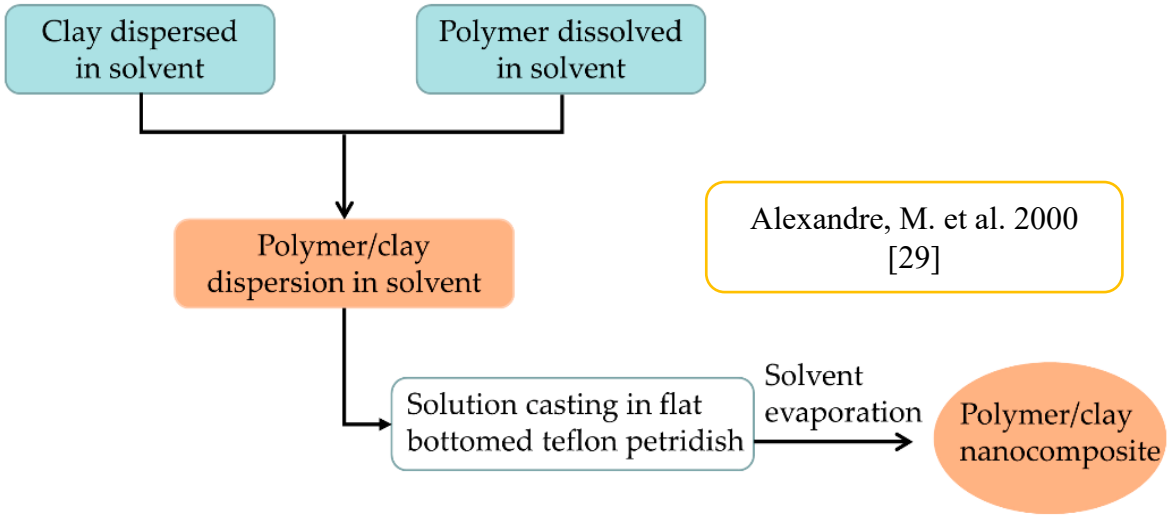

Clay dispersed in solvent
Polymer dissolved in solvent
Polymer/clay dispersion in solvent
Alexandre, M. et al. 2000 [29]
Solution casting in flat bottomed teflon petridish
Solvent evaporation
Polymer/clay nanocomposite

Figure 5. Solution-blending method scheme.

Table 1. Polymer/nanoclay composite made by solution blending. All these composites have an intercalated clay structure. PS: polystyrene

Nano clay	Polymer	Reference
Co-Al-LDH	Polystyrene	[30]
Cloisite 30B	Chitosan/polylactide	[31]
Mg-Al-LDH	Epoxy	[32]
Mg-Al-LDH	Acrylic resin	[33]
Cloisite and sepiolite	Hydrogenated nitrile butadiene rubber	[34]

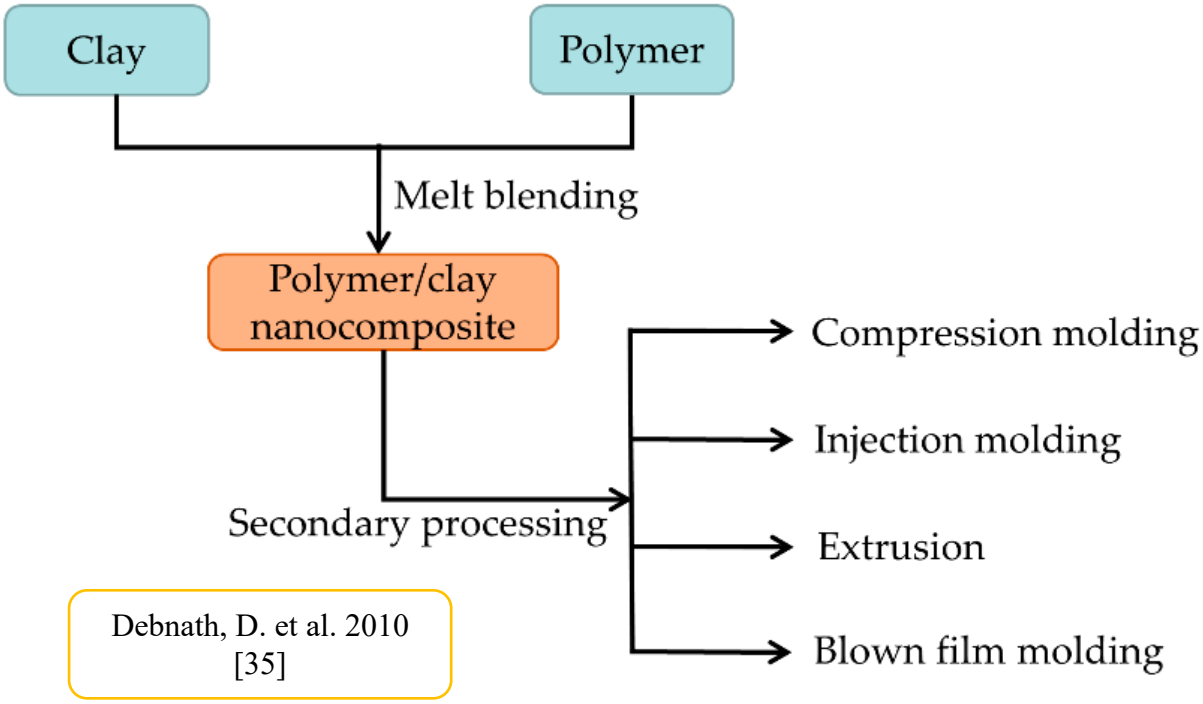


Figure 6. Melt-blending method scheme.

Table 2. Polymer/nanoclay prepared by the melt-blending method and dispersion states.

MMT: montmorillonite.

Nano clay	Polymer	Clay Structure	Reference
Cloisite 30B	Nylon 6	Intercalated	[36]
Na-MMT	Nylon 66	Disordered	[37]
Na-MMT	Epoxy	Intercalated	[38]
Na-MMT	Polyamide	Exfoliated	[39]
MMT	Polypropylene	Exfoliated	[40]
MMT	Polyvinyl chloride	Exfoliated	[41]

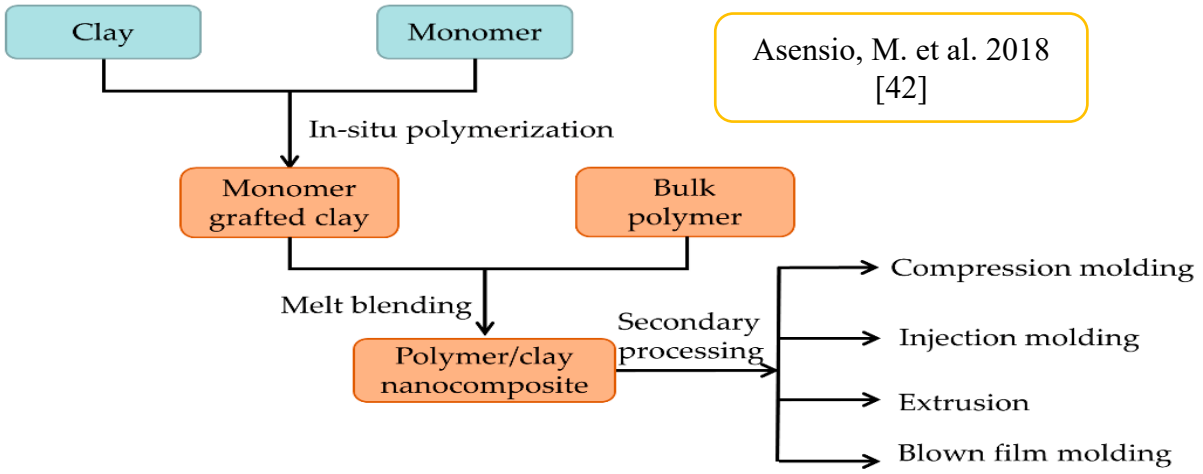


Figure 7. In-situ polymerization method scheme.

Table 3. Polymer/nanoclay prepared by the melt-blending method and dispersion states.

Nano clay	Polymer	Clay Structure	Reference
MMT	2,2,2-trifluoroethyl methacrylate	Exfoliated and intercalated	[43]
MMT	Bisphenol A polycarbonate	Exfoliated	[44]
Sepiolite	PP	Exfoliated and intercalated	[42]
MMT	PP	Exfoliated	[45]

The MMT Nano clay have been widely studied due to their high cation exchange capacity, swelling behavior, and large surface area [46-48]. Halloysite Nano clays are readily dispersed in various polymers without the need for exfoliation. This is due to there being less abundant hydroxyl groups on the Nano clay surfaces compared to MMTs [49]. The interfacial interaction between Nano clay fillers and polymer matrix, as well as the quality of Nano clay dispersion, has a significant influence on the performance of polymer/Nano clay composites [50].

3.2 Nanotechnology Application in Subgrade Engineering

The strength and durability of subgrade soils can be improved by incorporating different types of nanomaterial additives into traditional cement-based materials. Moreover, nanomaterials can stabilize subgrade soils and make them more durable and less erosive. Thus, it is necessary to review the mechanisms by which nanomaterials modify the physicochemical properties, mechanical properties and microscopic mechanism in subgrade soils.

3.2.1 Physicochemical Properties

Scholars have studied variations in the physicochemical properties of subgrade soils modified with different types and proportions of nanomaterial additives. Taha et al. [51] analyzed the effect of multi-walled carbon nanotubes and carbon nanofibers on stability of subgrade soils. Carbon nanomaterials fill the voids among soil particles and bond the particles together, which significantly increases the dry density of soil and reduces hydraulic conductivity. Chibuzor et al. [52] observed that the nanostructured palm beam ash had the properties of volcanic ash, which promoted the ion exchange and hydration reaction of soil particles, increased flocculation effect of stabilizers and could well enhance the stiffness of a high-expansive soil subgrade. Mohd et al. investigated the effects of different proportions of Nano clay, Nano alumina and Nano copper on engineering properties of different soils. Although the incompatible nanomaterials mixed with water cannot react with soil particles, nanoparticles with small sizes can fill the pores among soil particles, which increases the maximum dry density and reduces the contraction and expansion strain of subgrade materials [53]. Lv et al. [54] analyzed the stabilization effect of Nano silica particles with various sizes (e.g., 10 nm, 29 nm and 100 nm) on loess. The authors reported that the smaller the diameters of nanoparticles were, the smaller the large pores were, reflecting the filling and nucleation effects of nanoparticles. The results from infrared spectrum analysis showed that the chemical reaction between nanoparticles and soil particles mainly generated calcium silicate hydrate (C–S–H)

and calcium silicoaluminate hydrate (C–A–S–H) gels with chain structures, which effectively improved the stability of loess subgrades. Barhoum et al. [55] improved the plasticity of clay using calcite and Nano calcite. When the same Atterberg limit was achieved, the amount of Nano calcite was considerably lower than that of traditional calcite. Nano silica can promote hydration reaction, and the hydration products are densely distributed on the surface of soil particles and fill the pores in soil, which significantly improves the stability of the subgrade on soft soil [56]. Ugwu et al. [57] noted that cement and Nano chemical solutions interacted with clay particles when adding a mixture of 0.07% Terrasil Nano chemical solution clay and 4% cement in clay. The formation of permanent silicide in the interior and surface of soil particles improved the Atterberg limits. The permeability of shallow subgrade soil was almost zero, exhibiting a good anti-seepage effect. Polat et al. [58] found that Nano magnesia, as an expansion agent in cement paste, could promote the hydration reaction to produce a uniform and strong microstructure, which enhanced the filling effect in the capillary pores of cement. In summary, the addition of nanomaterials into different adverse subgrade soils will result in a series of physicochemical reactions among nanomaterials, soils and additives, which improves the engineering performances of subgrade soils. On one hand, nanomaterial can enhance the compactness and shear strength of soils by filling the voids among soil particles. On the other hand, nanomaterial promotes the hydration reaction of cement and ion exchange between soil particles. The gel structure formed on the surface of soil particles can densify the soil matrix and improve the subgrade soil. Therefore, how to accurately determine the physicochemical reactions according to the types of subgrade soil, nanomaterials and cement is one of key issues for future to research on nanomaterials as improved subgrade soil.

3.2.2 Mechanical Properties

Existing researchers have indicated that nanomaterials can enhance mechanical characteristics of subgrade soils and make them meet the needs for subgrade engineering. Azzam [59] attempted to apply polymer nanocomposite technology from a chemical perspective to increase the durability of expansive clay subgrade. Results showed that the expansion ratio of expansive clay with 15% nanocomposite was reduced by 90%, while stiffness was increased by 4.5 times and unconfined compressive strength (UCS) was increased by 2.2 times after 28 days of oxidation. Meng et al. [60] stated that the combination of fibers and nanoparticles effectively increases the strength of clay compared to use of a single type of glass fiber. When the proportion of fiberglass and Nano clay is between 0.5% and 1.5%, the shear strength of clay can be increased by 84% and stability of clay subgrade can be improved. Pusadkar et al. [61] added Nano copper into Black Cotton Soil to improve its mechanical behavior. The effects of Nano copper on UCS and expansion pressure of modified soil were also analyzed. The authors concluded that the optimal Nano copper content was 1.5%. At such a Nano copper content, the UCS was increased by 343.12% and the expansion pressure was decreased by 22%. Ewa et al. [62] successfully developed a Nano chemical material (i.e., Terrasil) as a stabilizer to improve the geotechnical performance of Ogoja subgrade. After addition of Nano chemical materials, the shear strength and California bearing ratio (CBR) of the soil were increased. In addition, the strength and stability of the whole subgrade soil were also enhanced. Moreover, Lin [56] mixed Nano silica with sewage ash and cement to improve the stability of subgrade on a soft soil. The UCS for soil was increased by 3–7 times at a sewage ash/cement ratio of 3:1 and a

Nano silica content of 2%. Yao et al. [63] analyzed the effect of Nano magnesia on stability of soft subgrade. The authors stated that when the cement content was 13% and optimal Nano magnesia content was 15‰, the UCS and ductility of cement-stabilized soil could be considerably improved. Onyelowe et al. [64] used Nano clay as an additive to modify soft subgrade in response to structural damages in southeastern Nigeria. The addition of an optimal proportion of Nano clay can significantly improve the plasticity and strength of soft red soil, meeting the requirement for subgrade materials. Kulkarni and Mandal [65] used the combination of fly ash and nanomaterials for the first time to treat expansive silty soil subgrade. When 30% fly ash and Nano solution were added into the soil, the CBR was greatly improved, and the coefficient of permeability was reduced by 86%. The UCS of Nano alumina and cement-modified disintegrated carbonaceous mudstone (NACDCM) rapidly increased and then gradually stabilized with increased Nano alumina content. The failure stress for nano-CaCO3 and cement-modified disintegrated carbonaceous mudstone (NCCDCM) under a confining pressure of 100 kPa increased with increased Nano calcium content (Figure 8).

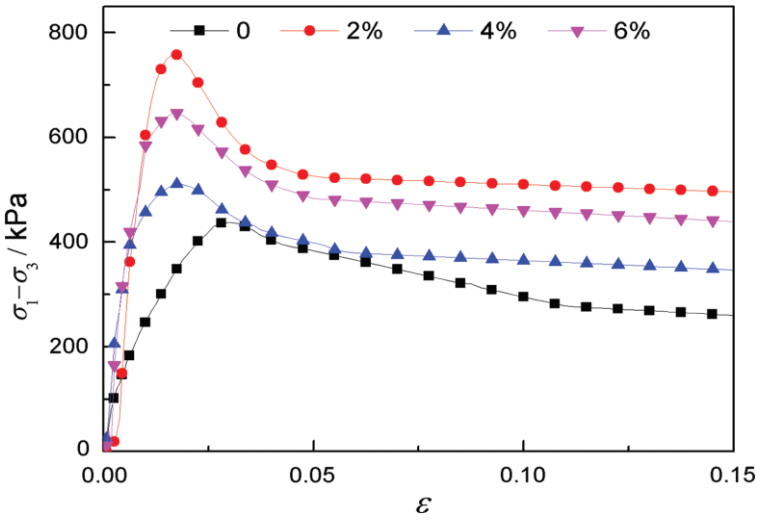


Figure 8. Stress–strain curves for NCCDCM at a confining pressure of 100 kPa.

Generally, nanomaterials can enhance the mechanical characteristics of subgrade materials. However, the effect of subgrade improvement is affected by various factors, such as soil type, additive type, nanomaterial content and target mechanical properties of soils. Hence, plenty of researches need to be conducted to select appropriate nanomaterials for improving the mechanical properties of subgrade soils and meeting the engineering application conditions.

3.2.3 Microscopic Characteristics and Mechanism

Nanomaterials improve the physicochemical and mechanical properties of subgrade soils mainly by reducing the microscopic porosity of the subgrade soil. Scanning electron microscopy (SEM) can observe the microstructure of soil before or after modification with nanomaterials, providing a method for revealing the mechanism by which nanomaterials improve subgrade soils. Many achievements have been made in studying the microscopic characteristics and modification mechanism for subgrade soils with nanomaterials. For

example, Ghavami et al. [66] analyzed by SEM the microstructure of weak kaolin modified with silica fume and Nano silica. The authors reported that Nano silica improved the microstructure of kaolin and filled the voids, and thus enhanced the compressive strength of subgrade materials. Majeed and Taha [18] revealed that the high specific surface area of nanoparticles had the effects on accelerating some microparticle reactions in the soil matrix and improving the strength and permeability of the soil. Anggraini et al. [67] studied the stabilization effect of sea-made clay with lime and Nano modified coir fiber. Under wetting conditions, nanomaterials can promote the pozzolanic reaction and the binding material is wrapped on soil particles, which improves the durability of stabilized soil. Furthermore, the reinforcement mechanism for Nano modified coir fiber was identified. Meng [60] revealed the mechanism by which Nano clay improved the tensile strength of clay when studying the effect of nanocomposites on the stability of clay soil. Firstly, Nano clay particles combined with water to produce a viscous gel material, which increased the friction between soil particles. Secondly, nanoparticles filled the voids between soil particles, increasing the effective contact areas between soil particles and improving the interfacial bond strength and friction. Finally, the mechanical properties of clay are effectively improved by the viscous gel fibers around soil particles. Maharsia and Jerro [68] confirmed that the Nano clay particles in the silty soil reacted with moisture to fasten the surrounding soil particles together. Moreover, Cui et al. [69] revealed the effect of Nano silica gel bonding with soil particles and fully filling the inter-particle voids by SEM. Nano silica can greatly improve the cohesion of silty soil and make the soil show better shear performances. Meng et al. [60] reported that the composite nano-CaCO3 can promote production of cement hydration products, reducing the long-term corrosion rate of marine environment to the cement-stabilized soil. Ghasabkolaei et al. [70] observed by SEM the microstructure of Nano silica- and cement-modified clay. The modified clay was denser and more uniform since silica had high pozzolanic effect and accelerated the cement hydration reaction. Most of the pores in clay are filled with nanoparticles and large voids at the interface of soil particles are reduced, which enhances the mechanical properties of the clay. The SEM images of the NACDCM with different Nano alumina contents are shown in Figure 9. The mechanism of reaction between nanoparticles and soil particles is shown in Figure 10. It is noted that Nano alumina not only fills the pores among soil particles but also generates complex cementitious materials by gel binding and chemical reaction with soil particles, and thus the

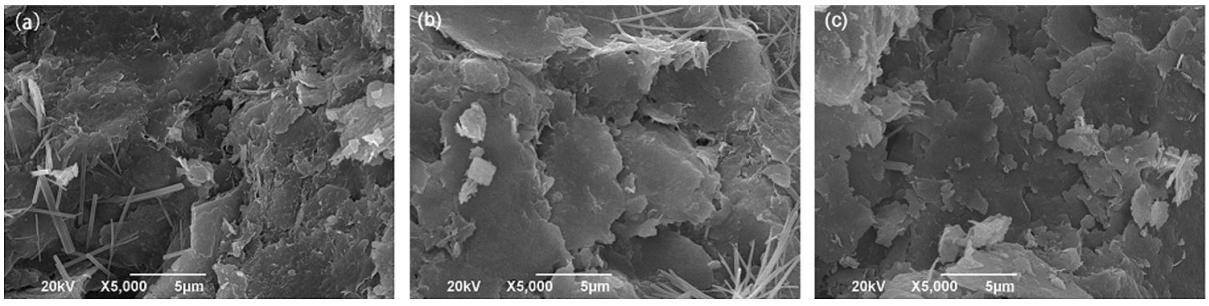


Figure 9. SEM images of NACDCM with different Nano alumina contents: (a) 0%; (b) 2%; (c) 6%.

mechanical properties of soil are effectively improved [71, 72]. Due the complexity, there is no unified view on the micromechanism by which nanomaterials modify subgrade soils to date.

Consequently, the microscopic characteristics of nanomaterial-modified subgrade soils and their related mechanism should be further studied.

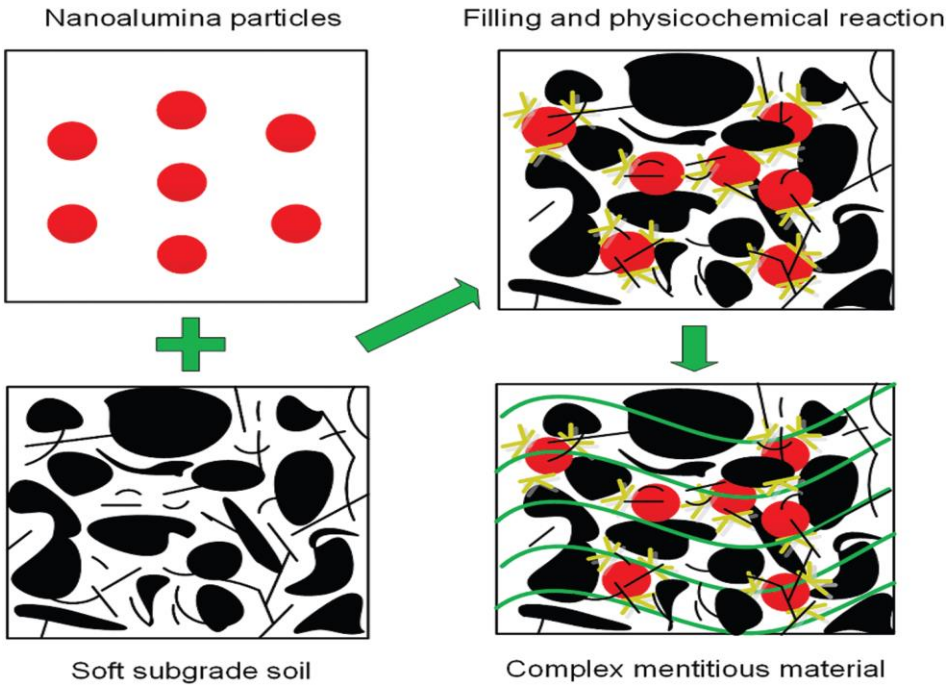


Figure 10. Mechanism by which Nano alumina improves the mechanical behavior of soft subgrade soil.

Nanomaterials can promote the hydration reaction of cement and improve the physicochemical and mechanical properties of subgrade soils. However, there are still some problems with application of nanomaterials in subgrade engineering: (i) agglomeration phenomenon seriously affects the efficiency of nanomaterials, so it is necessary to work out effective methods for evenly dispersed nanomaterials; (ii) modification mechanism for nanomaterials to improve the performance of subgrade soils is not very clear, so much effort should be made to this aspect; (iii) to ensure the long-term stability of the subgrade, researchers should focus on studying the effects of nanomaterials on durability of sulphate resistance, chloride penetration resistance and cyclic freezing–thawing of subgrade soils need to be studied in depth.

3.3 Nanotechnology Application in Pavement Engineering

Nanotechnology is not only widely used in subgrade engineering but also has a broad application prospect in pavement engineering. The unique physical and chemical properties of nanomaterials give them the potential to improve the properties (e.g., water stability, rutting resistance, fatigue resistance and optical properties) of pavement structures. In this section, the applications of nanotechnology in flexible pavement and concrete pavement are reviewed.

3.3.1 Flexible Pavement

Nanotechnology is utilized extensively to improve the performance of flexible pavements. Many studies [73, 74] have demonstrated that nanomaterials have significant effects in improving the engineering properties of asphalt binder and mixture. Saltan et al. [75–77]

modified asphalt with a variety of nanomaterials and found that the modified asphalt has better uniformity and water stability, as well as higher rutting resistance and fatigue resistance. Compared with other nanomaterial-modified asphalt binder, Chen and Zhang [78] observed that asphalt binder modified with 1% Nano rubber powder has a higher resistance to fracture and rutting when encountering a low temperature. Jamshidi et al. [79] studied the modification effect of different nanomaterials on asphalt binder, and then used the activation energy theory to analyze the influence of nanomaterials type and content on intermolecular forces.

The asphalt aging process is actually the process of chemical reaction on functional groups inside the asphalt material. During the process, some of the original functional groups will be reacted, and some new functional groups containing the carbonyl group will be produced. Yao et al. [80, 81] proved that nanomaterials have an anti-aging impact on the asphalt by comparing the changes in the content of these six functional groups. Researchers [82, 83] revealed the anti-aging mechanism of organic-modified and Nano-montmorillonite modified asphalt. Nanozycosoil and Nano clay can be used as anti-aging agents to increase the adhesion of asphalt, and polymer composites modified with nanomaterials form three types of structures (Figure 11), which show impacts on final properties of the composites. Furthermore, the nanomaterials improve the mechanical properties (e.g., rutting resistance and stiffness modulus) and water sensitivity of asphalt mixtures [84–86].

Apart from enhancing the mechanical properties, nanotechnology can also change the optical properties of asphalt to overcome the challenge of rutting on asphalt pavements. Wang et al. [87] used a nanoparticle-filled polymer composite to reduce the absorption of solar energy by asphalt pavement and thereby controlling the temperature of pavement. The experiments on different nanoparticle-filled polymers indicated that the Nano- TiO2/acrylic composite have the highest solar reflection efficiency and best pavement temperature reduction effect. In addition, the application of nanotechnology allows asphalt pavements to remove vehicle emissions. For instance, Chen and Liu [88] used the photo catalysis of nano-TiO2 to remove NO*x* from vehicle emissions and systematically investigated the influences of surface friction, humidity and light intensity on NO*x* removals. The experimental results showed that nano-TiO2 can make the NO*x* decontamination rate of asphalt pavement reach 6% to 12%, and the environmental purification effect was superior.

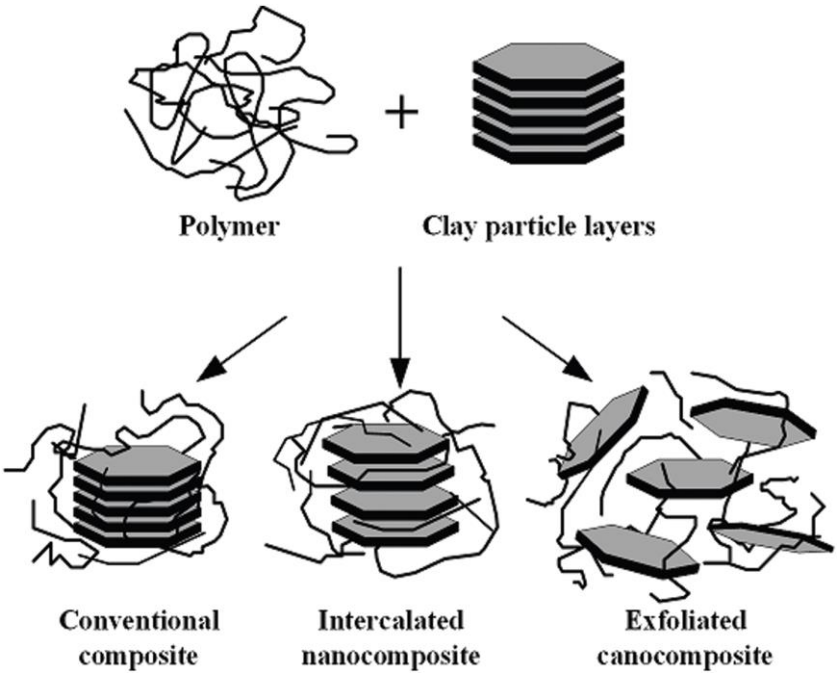


Figure 11. Schematic diagram of structures of polymer nanocomposites.

3.3.2 Rigid Pavement

The performance of concrete pavements is closely related to the structure at micro-Nano scales. Therefore, nanotechnology has the potential to give new properties to concrete or enhance the performance of concrete, showing great implications to concret transportation infrastructure. Nowadays, many countries are working to promote the development of nanotechnology-based concrete materials. For example, the United States has proposed a national technology roadmap in this field [89].

The synthesis and assembly of materials at the nanoscale offer the possibility for development of new cement additives. Nano silica is a promising Nano modifier, and the mechanical properties of cement paste and porous concrete will be improved by incorporating Nano silica with proper composition [90–93]. Because Nano silica enhances the interface between paste and aggregates, the strength of Nano silica-modified concrete would be further enhanced by incorporating Nano silica in the cement mixture [94]. Further research on the same [95] showed that Nano silica behaves as not only a filler for improving the microstructure but also an activator for promoting the pozzolanic reaction.

Gonzalez et al. [96] found that the surface friction and sound absorption of concrete pavements have been enhanced by incorporating Nano silica into concrete. After coating the top of the textured concrete surface with Nano coated lotus leaves, the modified concrete pavement can maintain the required surface friction on rainy days [97]. Schematic diagram of Nano coated lotus leaves is shown in Figure 12. The texture characteristics of the Nano silica-modified concrete pavement surface have also been investigated. With increased Nano silica content, 3D texture indices increased correspondingly, which indicates that Nano silica can improve the abrasion resistance and frictional property of concrete surfaces [98].

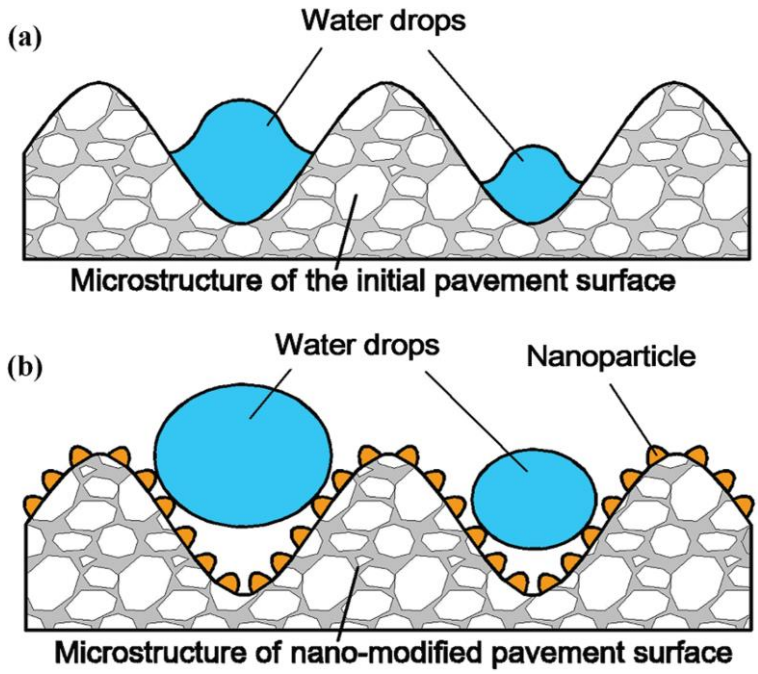


Figure 12. Schematic diagram of Nano coated lotus leaves: (a) initial pavement surface; (b) Nano silica-modified pavement surface.

Pacheco-Torgal et al. [99] summarized the mechanism for nanomaterials improvement of strength for cementitious composites. The nanoparticles acted as kernels in cement, which decreased the Ca(OH)2 crystal size. The smaller crystal contributes to the hydration reaction of Portland cement and fills the pores of the calcium silicate hydrate structure, leading to the denser concrete.

The addition of nanomaterials also opens up new capabilities for concrete pavements. It was shown that the addition of nanophosphors enabled concrete luminescent after exposure to light, which brings convenience to the traffic at night [100]. Meanwhile, it was also found that the pavement load affects the luminescence decay rate for nanomaterials-modified cement pavement.

Conclusively, the appearance of nanotechnology has great influence on the world, and its effect on pavement engineering is far-reaching. Moreover, nanotechnology will help to develop materials with fresh characteristics and excellent functions to meet the needs for pavement engineering. Adding nanomaterials can improve the physicochemical and mechanical properties of pavement materials. However, the application of nanotechnology in pavement engineering is still not perfect, and it is necessary to conduct in-depth research and exploration from the following three aspects: (i) nanostructured systems with specific properties need to be designed and synthesized, and frontier preparation techniques for pavement nanomaterials deserve to be developed; (ii) the formation, structure and properties of pavement modified by nanomaterials and effects of nanomaterials on macroscopic behaviors of pavement should be studied on the nanoscale or atomic scale, and their physical and chemical effects caused by surface, interface and structure are yet to be analyzed; (iii) application research and industrial production of pavement nanomaterials need to be optimized. In brief, nanomaterials and nanotechnology provide a good opportunity for development of pavement materials and their

engineering applications. There will be considerable development in the material behavior mechanisms and pavement functionalization.

3.4 Advantages of Nanomaterials Compared with Traditional Materials

The aforementioned nanomaterials used in subgrade and pavement engineering can significantly improve the engineering properties of materials. Moreover, compared with traditional subgrade and pavement materials, nanomaterials exhibit advantages in environmental disturbance, environmental friendliness, cost and durability.

3.4.1 Environmental Disturbance

Subgrades disasters (excessive deformation and slope instability) often occur during construction or operation. Traditional methods for subgrades reinforcement are mainly classified into four types, i.e., densification, replacement, drainage and grouting [101]. However, these traditional methods have shortcomings in on-site processing and bring about strong interferences to the circumjacent living environment. Grouting is the injection of pumpable materials into weak soils or rocks to change their physicochemical characteristics, which can improve mechanical properties, integrity and compactibility of rocks and soils [102, 103]. Nevertheless, grouts require high pressure to enter the target formation and thus reinforce the weak foundation after curing or forming gel. The mean particle size for Ordinary Portland cement is 20 μm approximately, which causes cement paste to be unstable with poor potability [104, 105]. Compared with conventional binding materials, nanomaterials have smaller particle sizes and can easily penetrate into rock and soils with low porosity. A soil reinforcement method that is a mixture of nanomaterials and water is slowly grouted from the edge of the injection point and conveyed into the target strata with groundwater flow can efficaciously improve the mechanical strength of soil [106, 107]. Compared with traditional high-pressure grouting, the method does not need high pressure and can significantly reduce interference on residential environment [108]. This new method is used in not only highway subgrades but other shallow foundations.

3.4.2 Environmental Friendliness

Portland cement widely used as a binding agent for concrete is a significant building material for subgrade strengthening [109]. The cement manufacturing industry has created enormous environmental challenges. Portland cement is mainly made by calcining limestone, clay and iron ore powder. This process typically consumes a good deal of energy and produces large amounts of oxide such as carbon dioxide (CO_2), sulfur oxides, and smog [110]. A number of studies have suggested that the global cement industry's carbon dioxide emissions account for about 5% of total anthropogenic emissions [111, 112]. In addition, the traditional cementitious materials represented by cement will be unfavorable to the ecological environment of construction project area, which is manifested by ecological problems, such as reduced vegetation and bio-chain breakage [113]. The chemical slurries (e.g., sodium silicate, ethoxyline resin, and acrylate) are solution-type paste wit h high irritability, which can be injected into fine cracks [114, 115]. However, if not handled properly, chemical slurries can cause fearful damage and pollution to surrounding buildings and groundwater. Moreover, chemical slurries are very expensive and the strength of solidified grout stone is lower than that

of cement pastes, so the application of chemical slurries is also limited [116, 117]. For instance, ethoxyline resin is insoluble in water but is soluble in organic solvents such as aromatic hydrocarbon, ketone or alcohol. Organic solvents, however, are volatile and have high price. Some polymer material solvents have the disadvantages of being toxic to the environment, and they are flammable and dangerous. On the contrary, most nanomaterials are generally non-toxic and have a stable chemical property, and they not only can improve the engineering properties of subgrade rock and soil but also are conducive to the growth of slope vegetation. The viscosity, rutting and fatigue resistances of asphalt mixtures are often deeply enhanced by adding nanoparticles [118]. The influence of nanoparticles on soil development and their effect on soil structural behavior have also been studied for decades [119]. Nowack and Bucheli [120] analyzed the effects of nanoparticles on the environment. The author stated that nanoparticles have little impact on environmental flora and fauna at low concentrations. A consensus is emerging that nanomaterials cause relatively low risk to the environment after numerous research on transformations, bioavailability, toxic and environmental effects of nanoparticles [121]. Therefore, it is secure and environmentally friendly to take advantage of nanomaterials to improve the weak subgrade.

3.4.3 Cost

Cost is an important consideration when choosing construction materials. Nevertheless, since the total cost is relevant to unit material price, dosage, job practice, construction equipment, construction effect, environmental influence, etc., it is difficult to accurately estimate cost [122, 123]. Some scholars comprehensively considered the benefits and cost requirements and defined the price/performance ratio as a comprehensive evaluation index. In terms of the price/performance ratio, although nanomaterials have a higher univalence, a handful of nanomaterials are merely needed for effective reinforcement [124]. The comparison between traditional materials and nanomaterials in terms of price/performance ratio for soil treatment is analyzed. It shows that the price/performance ratio of nanomaterials is low or medium, while that of epoxy is high. Not long in the future, the cost of nanomaterials will likely decline with advancement of production technologies and fabrication processes. Based on the global investments shares in development of nanomaterials and updates on nanotechnology, Roco [125] estimated that nanotechnology, in terms of basic knowledge and infrastructure for application areas, will be developed rapidly between 2000 and 2020. Therefore, the cost will not become an obstacle to the advancement of nanotechnology, and nanomaterials will be more widely used in subgrade and pavement engineering.

3.4.4 Durability

In subgrade and pavement engineering, the materials durability is significant for proper functioning of subgrade and pavement structure [126]. In recent years, the durability of cementitious materials has attracted more researchers' interests than their mechanical behaviors [21]. However, it is difficult to accurately evaluate the effectiveness of measures to improve the durability of materials. This is from the following two reasons: (i) improvement measures of material durability in the existing studies are mainly carried out in the laboratory, so it is difficult to judge the application effect of the actual engineering; (ii) even for the limited on-site practice, it is difficult to conduct a decades-long test on performance of actual

engineering structures [120]. Here are some examples of durability of subgrade pavement engineering materials in the literature.

Existing researches indicated that CaCO3/polymer nanocomposite is a fully compatible and efficient material used to reinforce limestone monuments in art and architecture. It can enhance the durability of aging limestone and improve the UCS of stone compared with samples dealt with acrylic copolymer without nano-CaCO3 [127, 128]. To reduce the premature failure of bridge deck pavement concrete in frigid areas, a certain amount of Nano silica was added to bridge deck pavement for improving the concrete durability [129]. The results showed that Nano silica availably assimilated the calcium hydroxide released in the initial stage of cement hydration, raising the content of calcium silicate hydrate and enhancing the interfaces between slurry and aggregates from the hardened cement. Singh et al. [130] studied the durability of Nano engineered fly ash concrete. The combination of Nano silica particles in concrete results in the increased durability and working life. Moreover, the performance of concrete incorporated with Nano silica particles is significantly improved compared to control specimens with Nano silica. Akbari and Modarres [131] confirmed that a proper amount of Nano clay and Nano lime improves the hot mix asphalt durability for both limestone and granite aggregates. Conclusively, the durability of subgrade and pavement structure can be effectively improved by adding Nano-materials to soil, concrete and asphalt materials.

Nanomaterials show good performance in improving soil properties, including physicochemical and mechanical properties. Moreover, flexible and concrete pavement improvement by nanotechnology have higher rutting resistance, fatigue resistance, and mechanical properties, due to the size effect of nanomaterials. The application prospect of nanotechnology in subgrade and pavement engineering is summarized in Figure 13. It shows that nanomaterials play a promising role in improving the properties of subgrade and pavement materials, as benefiting from their environmental friendliness, lower environmental disturbance, better price/performance ratio and higher durability.

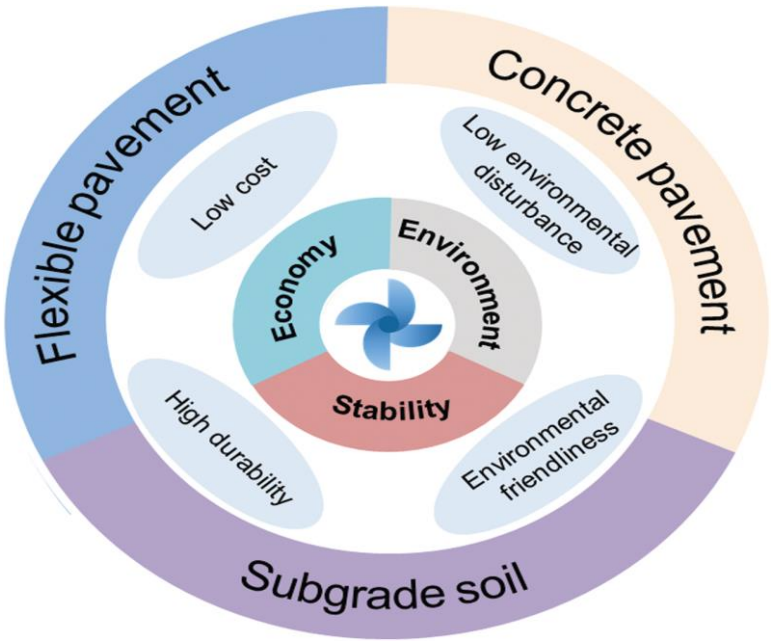


Figure 13. Application prospect of nanotechnology in subgrade and pavement engineering.

4. Research Gap

Nano-clay composite materials can promote the chemical reaction and improve the physicochemical and mechanical properties of subgrade soils. However, there are still some problems with application of Nano-clay composite materials in subgrade engineering:

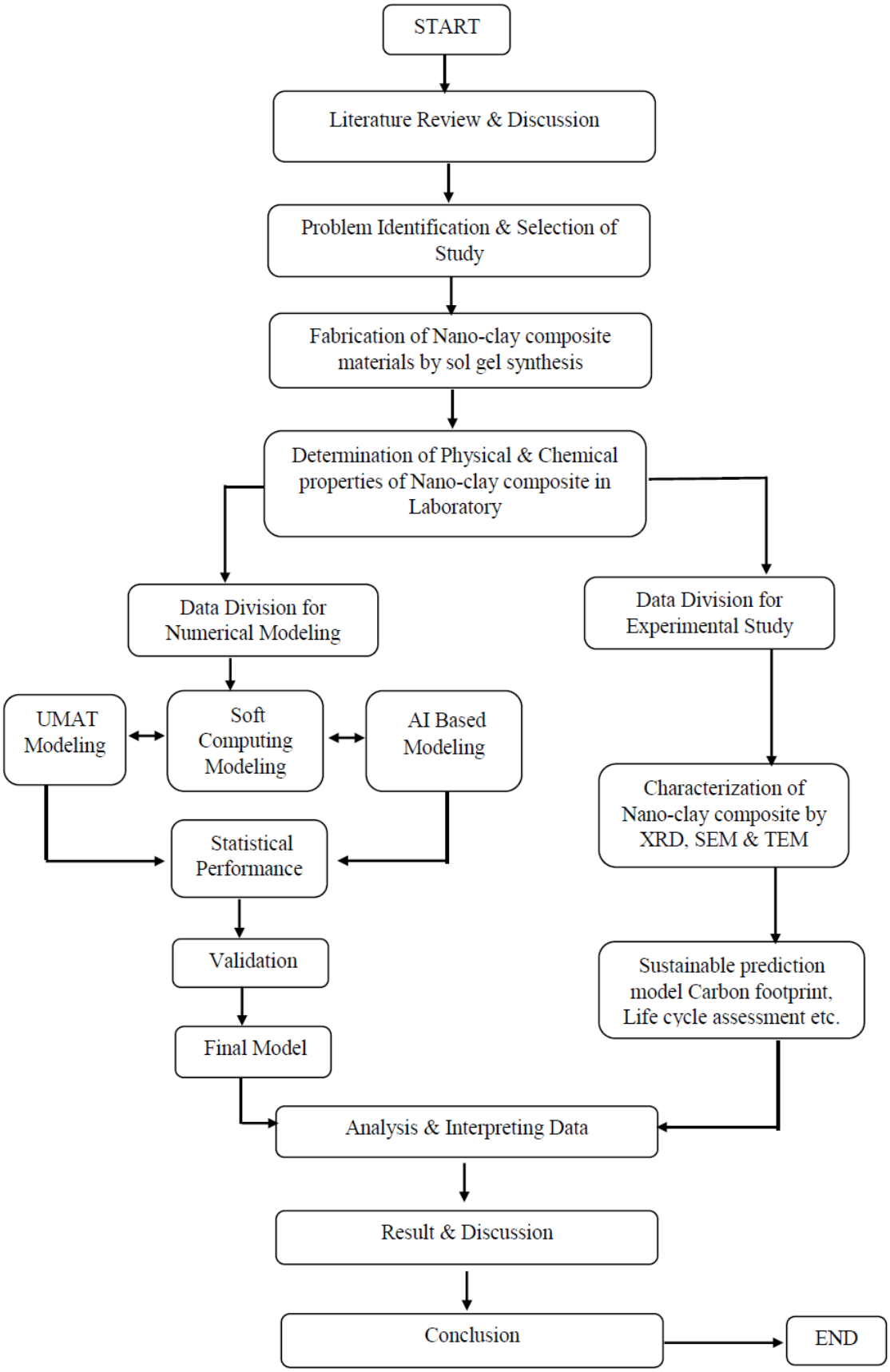
(i) Agglomeration phenomenon seriously affects the efficiency of Nano-clay, so it is necessary to work out effective methods for evenly dispersed nanomaterials.
(ii) Modification mechanism for nanomaterials to improve the performance of subgrade soils is not very clear; so much effort should be made to this aspect.
(iii) Predictive modelling of swell-strength of Nano-clay composite materials need to be studies using artificial intelligence approaches.
(iv) Numerical simulation of intelligent compaction for subgrade construction is also a new field to elaborate.

5. Research Objective(s)

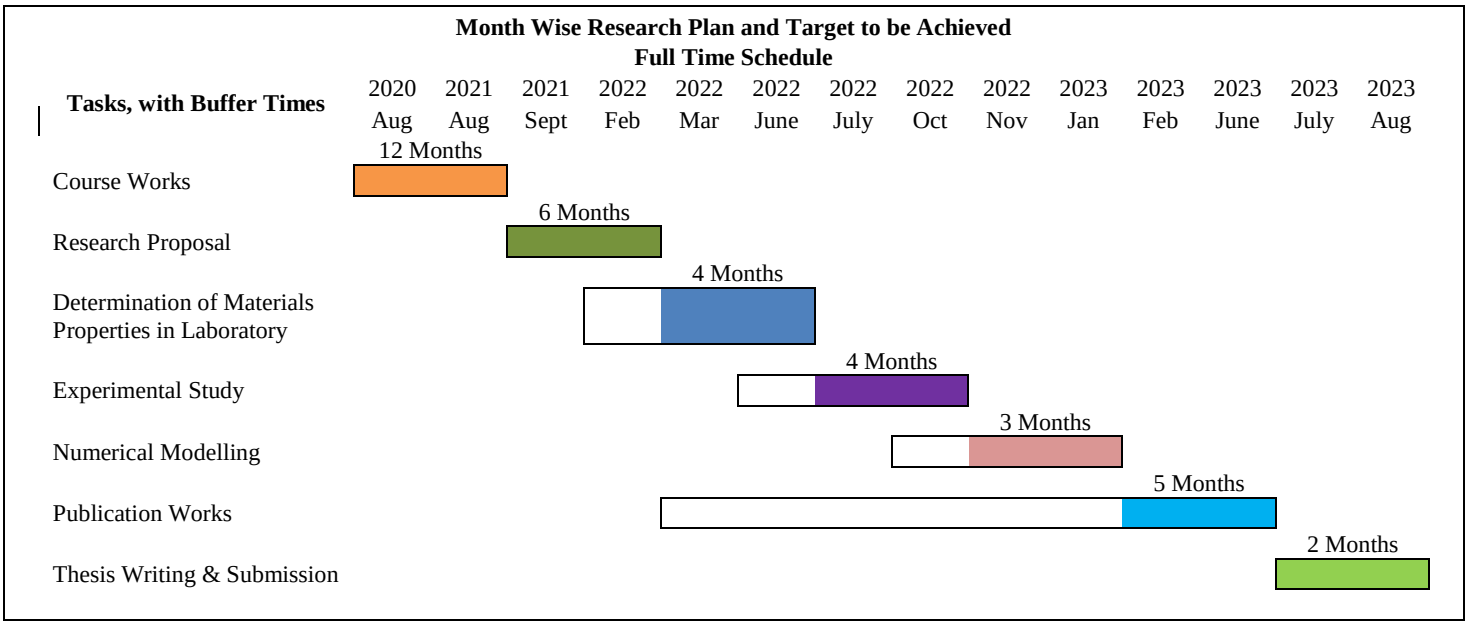
Expansive soils are problematic due to the performances of their clay mineral constituent, which makes them exhibit the shrink-swell characteristics. The shrink-swell behaviours make expansive soils inappropriate for direct engineering application in their natural form. In an attempt to make them more feasible for construction purposes, numerous materials and techniques have been used to stabilise the soil. Therefore, present investigation is undertaking with the following objectives:

1. Micro mechanism Nano-clay-modified soil techniques will be used with respect to their efficiency in improving the engineering properties of soil subgrade.
2. Characterization of the prepared Nano-clay composite materials with the help of engineering properties, XRD method for structural characterization, SEM for smooth surface study and TEM for grain size calculation.
3. Development of predictive model of swell-strength of Nano-clay composite materials using artificial intelligence approaches.
4. Numerical simulation of intelligent compaction for subgrade construction using UMAT in ABAQUS software.
5. Develop sustainable prediction model of Nano-clay composite materials in highway construction.

6. Research Methodology and Approach


START
Literature Review & Discussion
Problem Identification & Selection of Study
Fabrication of Nano-clay composite materials by sol gel synthesis
Determination of Physical & Chemical properties of Nano-clay composite in Laboratory
Data Division for Numerical Modeling
Data Division for Experimental Study
UMAT Modeling
Soft Computing Modeling
AI Based Modeling
Characterization of Nano-clay composite by XRD, SEM & TEM
Statistical Performance
Validation
Sustainable prediction model Carbon footprint, Life cycle assessment etc.
Final Model
Analysis & Interpreting Data
Result & Discussion
Conclusion
END

7. Month –wish Plan of Work and Target to be Achieved



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1 1. Introduction Nanotechnology is a new subject focusing on nanoscale world, which was first proposed by American physicist Richard Feynman in a speech in 1959 [1-2]. Nanotechnology is an extension of sciences and technologies that deal with particles less than 100 nm (Figure 1) [3– 5]. Because of fine particle sizes, nanomaterials have unique structural characteristics compared with traditional materials for soil reinforcements. Nanomaterials can produce four effects (i.e., size, quantum, surface and interface effect) and have been widely used in the fields of information, materials, energy, environment, medical and health, biology and agriculture [6]. There are two approaches, i.e., macroscopic materials broken down into nanometer-sized substances (top-down) and atomic or molecular components reconstructed into nanomaterials (bottom-up) (Figure 2) [7]. With rapid development of nanotechnology and superior performance of nanomaterials, nanomaterials (e.g., Nano silica, Nano clay, Nano alumina, nano-titania and nanotubes) have been introduced to improve subgrade and pavement materials. The use of nanomaterials in subgrade and pavement engineering is very significant since nanomaterials can modify various types of construction materials and additives. In subgrade engineering, seasonal repeated rainfall puts the subgrade under cyclic drying/wetting conditions, which leads to continuous disintegration and strength degradation of subgrade rocks and soils [8–10]. Previous studies [11–14] have shown that cyclic drying/wetting can cause shear strength reduction and excessive wetting deformation of geomaterials (Figure 3). Nanotechnology provides a means for building durable and low-maintenance highway infrastructure [15]. In subgrade engineering, nanotechnology is usually applied in two aspects: (1) analysis of soil structure from nanoscale to better reveal the subgrade performance mechanism with diverse nanostructures; (2) improvement of performance of subgrade soils from nanoscale by using nanomaterials as admixtures [16–18]. In pavement engineering, nanotechnology is mainly applied to flexible pavements and concrete pavements. The viscosity, rutting and fatigue resistances of asphalt mixtures are often enhanced deeply by adding nanoparticles [19]. The existence of nanoscale pozzolans, for instance, Nano silica, can help to achieve more dense microstructural packing and more impermeable cement matrix [20]. The mechanical properties (e.g., compressive strength, flexural strength, tensile strength) and durability (e.g., abrasion resistivity, freezing–thawing resistance) of concrete can be enhanced by Nano silica [21]. Although many studies have been conducted to improve material properties with nanomaterials in civil engineering, there is still lack of review work on application of nanomaterials in subgrade and pavement engineering. Figure 1. Soils viewed at different scales.
2 Figure 2. Synthesis and assembly approaches for nanostructured material. Figure 3. Schematic diagram of instability of an embankment slope. 2. Problem Statement It is known that due to isomorphous substitution, clay particles consist of superficial negative charges [22-23]. As a result, electrostatic forces exist between the negative clay surface and exchangeable cations within the clay-pore fluid media whose strength is dependent on the chemistry of the exchangeable cation [22]. In order to maintain neutrality within the clay-pore fluid media, there is a natural affinity for the counter ions to be attracted onto the surface of clay particles, thereby decreasing their concentration with distance from the clay surface. This change in concentration produces the surface electrostatic property known as the diffuse double